Advanced Climate Systems for EV Extended Range

(ACSforEVER)

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Hanon Systems

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Project ID # VS135

Overview

Timeline

Project Start: Oct. 2013

Project End: Jan 2017

Percent Complete – 70%

Barriers/Challenges

- EV market adoption
- Minimize climate system impact on vehicle energy storage system
- Extended range across broad selection of ambient environments

Budget

Total project funding: $4.68M

- DOE share $2.34M
- Contractor share $2.34M

Funding received in FY15: $ 0.7M

Funding for FY16: $ 0.5M

Project Partners

- Hyundai America Technical Center
  - Vehicle Integration and Testing
- National Renewable Energy Laboratory
  - CAE Modeling and Test Support
- Hanon Systems
  - Project Lead

Relevance – DOE Support

Vehicle Technologies Program Goals:

- Develop more energy-efficient and environmentally friendly technologies…and enable America to **use less petroleum and reduce GHG** (greenhouse gases).
- Further **development and validation of models** and simulation tools to predict the performance of advanced conventional and electric-drive vehicle systems.
- Support **EV Everywhere Grand Challenge** through DE-FOA-000793 Area Of Interest 11 - Climate Auxiliary Load Reduction focus areas:
    - **Advanced HVAC Technologies** to achieve passenger comfort with reduced auxiliary loads
    - **Cabin Pre-conditioning** while connected to the grid to reduce the amount of energy needed from the battery upon initial vehicle operation to either pull-down (hot conditions) or raise (cold conditions) the temperature in the cabin
    - **Energy Load Reduction and Energy Management** to reduce thermal loads that the systems must address

Relevance – Project Objectives

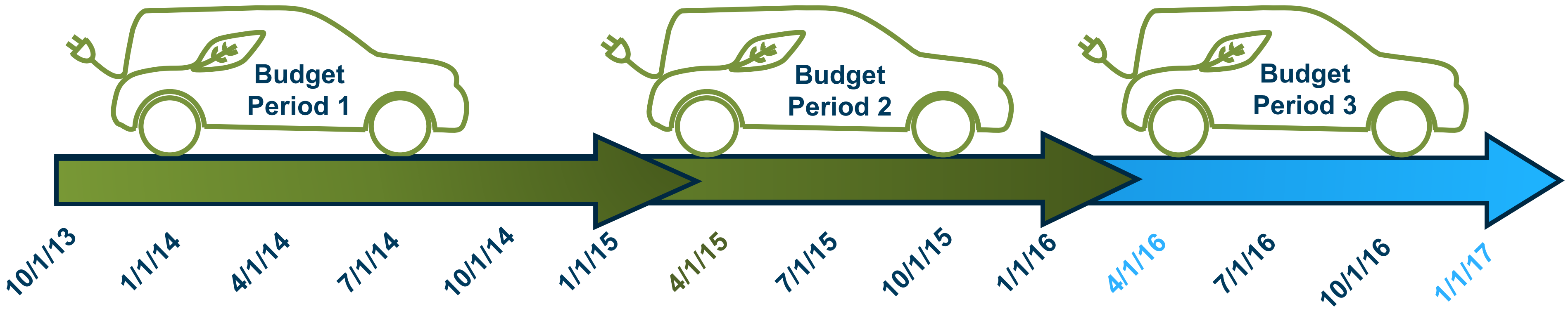
ACSforEVER project support of DOE VTP goals through:

- Overall objectives:
  - Extend electric vehicle range
    - Reduce climate energy usage from vehicle ESS
    - Development and validation of modeling tools
    - Technical areas of focus:
      - » Cabin pre-conditioning
      - » Thermal energy storage
      - » Refrigerant system efficiencies
  - Maintain occupant comfort

- FY15/16 objectives:
  - Refine system architecture
  - Design, fabricate and install new hardware
  - Complete evaluation of new hardware
  - Further understand limits of comfort model

ESS = energy storage system

Technical Approach



FY13/FY14 Tasks

- Select vehicle
- Define test conditions
- Define performance targets
- Complete baseline testing
- Develop & correlate models
- Define climate system architecture

FY15 Tasks

- Design componentry
- Fabricate hardware
- Bench test components & subsystems
- Analyze results to model predictions

FY16 Tasks

- Test baseline vehicle
- Integrate new climate system into vehicle
- Validate climate system performance impacts
- Analyze results to model predictions

Milestones

Budget Period 1: Subsystem Design and Specification Development Complete

Month/Year	Milestone	Type	Description
Sep-2014	Baseline Vehicle Testing	Technical	Completion of baseline vehicle testing in a wind tunnel.
Mar-2015	System Architecture Complete	Go/No Go	Completion of system architecture design for each subsystem to verify established system requirements are met

Budget Period 2: Design, Fabricate, and Validate Complete

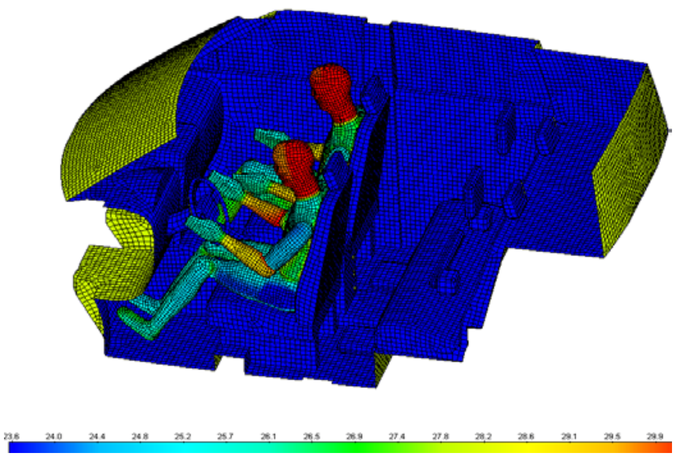
Month/Year	Milestone	Type	Description
Apr-2016	Bench Testing	Go/No Go	Subsystems testing to verify established system requirements are met

Budget Period 3: Integration and Vehicle Validation

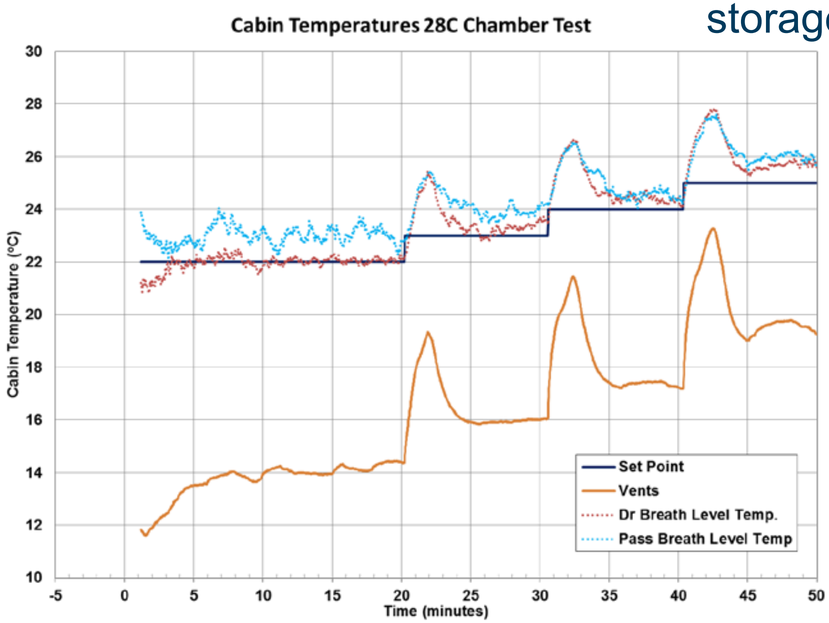
Month-Year	Milestone	Type	Description
Aug-2016	Vehicle Integration	Technical	All subsystems integrated into vehicle and ready for testing
Dec-2016	Vehicle Demonstration	Technical	Demonstration vehicle testing complete

Accomplishments
Cabin & Comfort Modeling

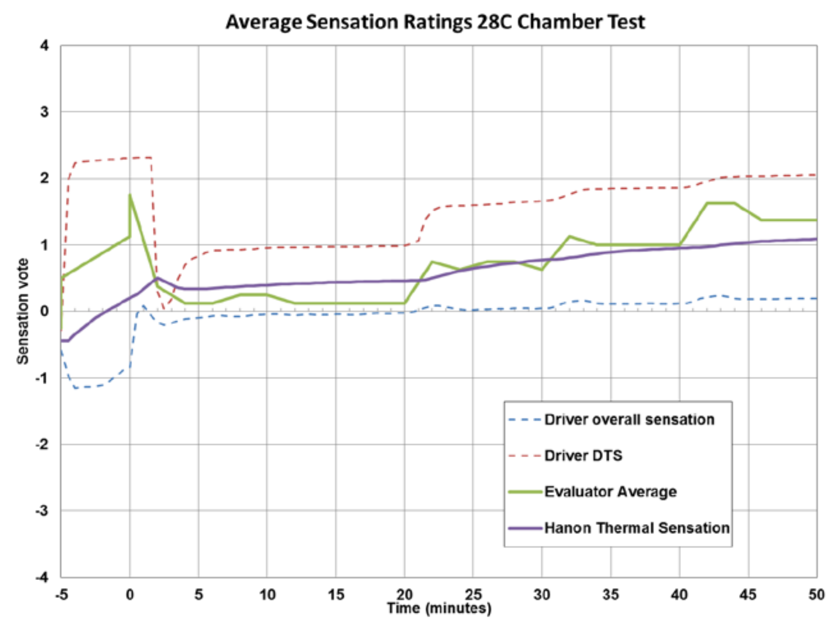
Model Development and Correlation



- The 3-D cabin CFD and comfort model was used to evaluate the effect of small changes in cabin set point temperatures.
- It was found that neither the Berkeley nor the Fiala models adequately predicted the effects of small cabin temperature changes on thermal sensation.
- A new thermal sensation metric, which is a combination of Berkeley and Fiala results was developed.
- Results were used to aid the evaluation of some of the range extension and ideas such as maximizing thermal storage.

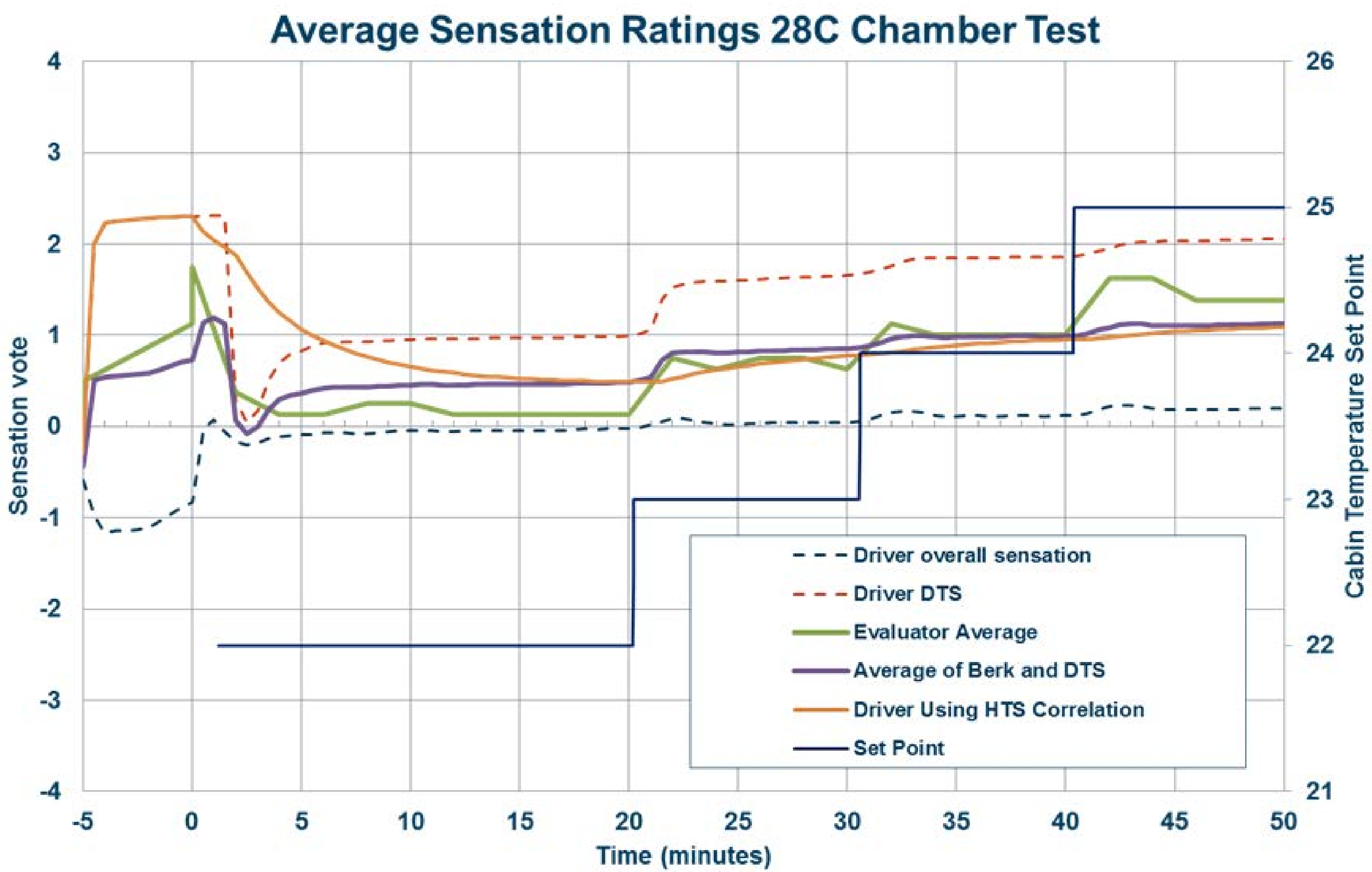


+28˚C Cabin Temperatures



+28˚C Occupant Thermal Sensation

Accomplishments
Additional Model Predictions



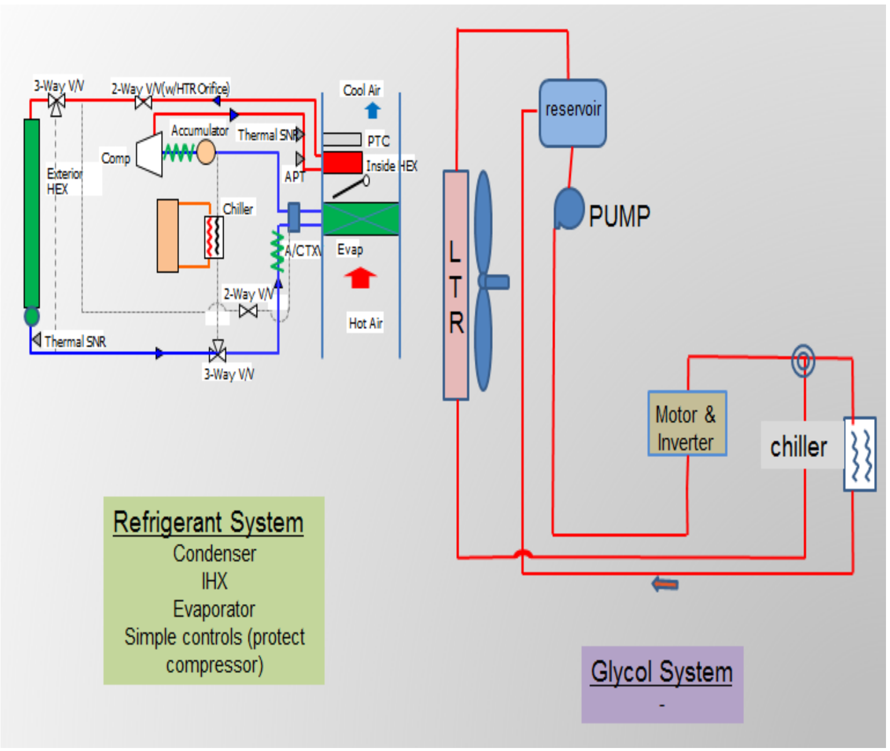
A tool is needed to predict comfort impact given small changes in interior cabin temperature, allowing the power savings to be translated to range improvement

Accomplishments
Cost Analysis

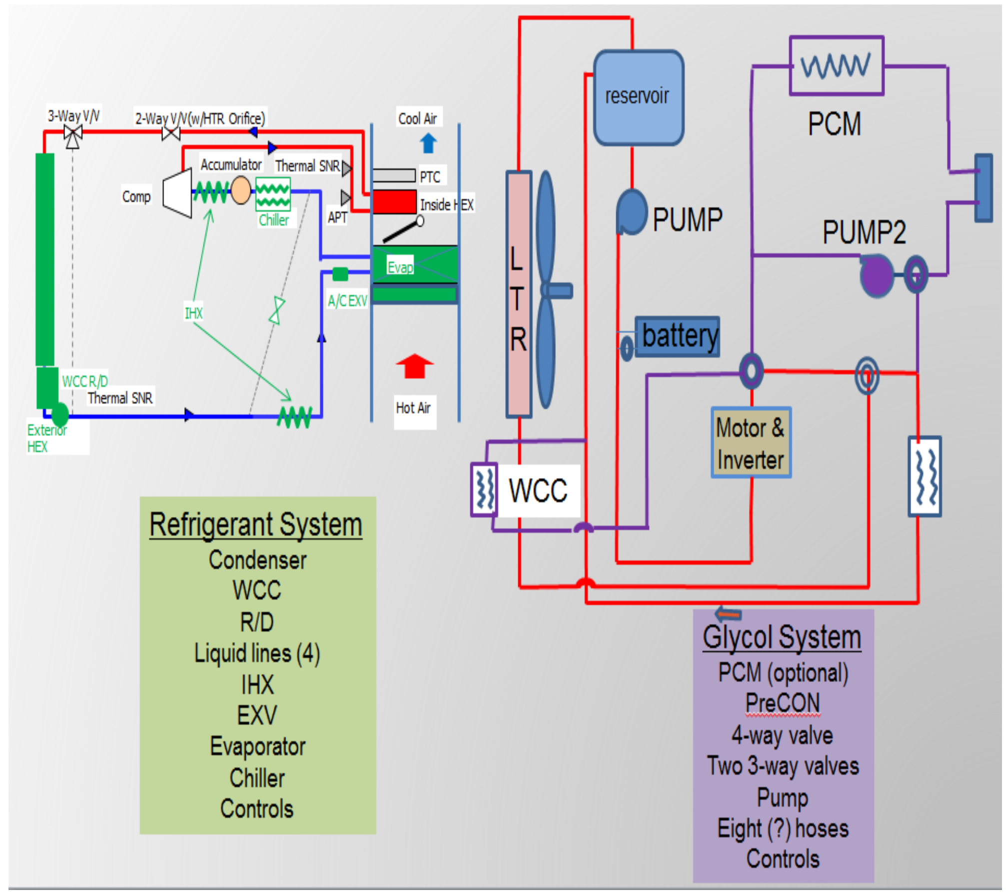
Levels of modifications for A/C and Heat Pump being developed

For Example:

Minor Modification



Major Modification



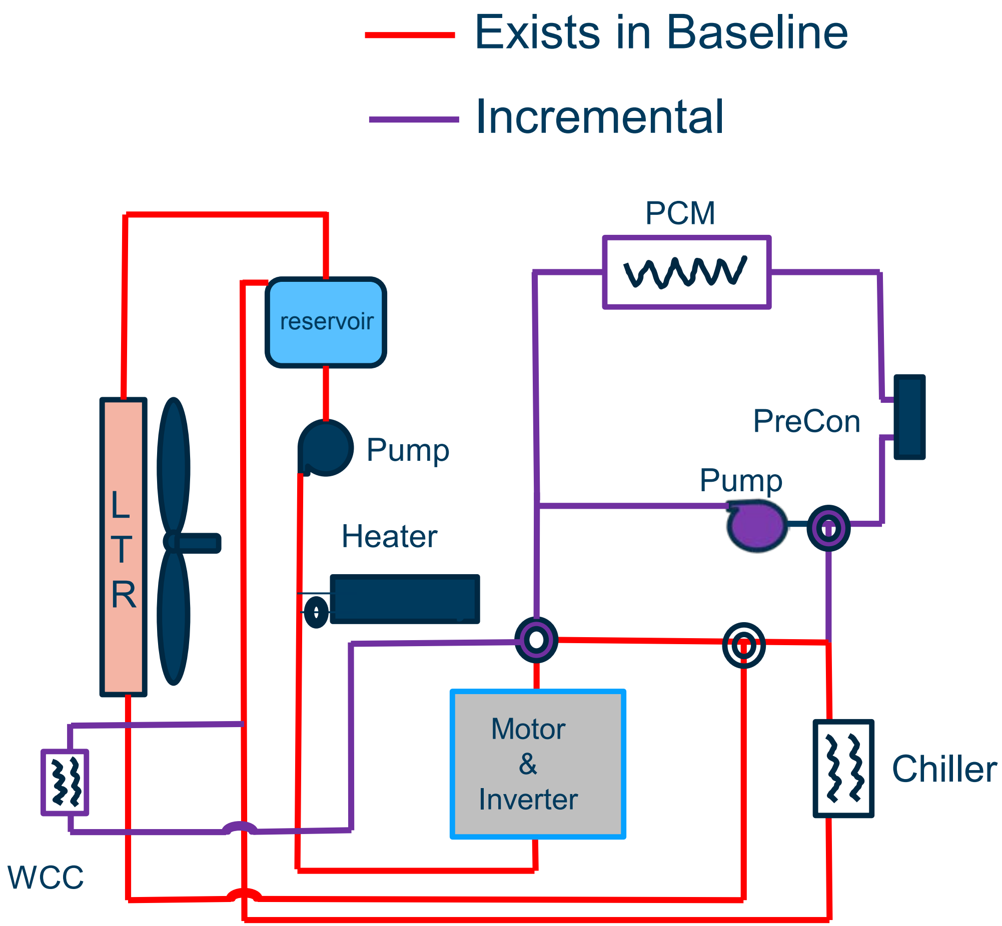
Accomplishments
Addressing Shortfalls

Areas for improvement identified in FY14

- Problem: At 5°C there is very low/no baseline PTC power consumption
  - Solution: Introduction of a pre-conditioning (PreCon) heat exchanger in the HVAC that transfers heat directly from thermal storage to the cabin

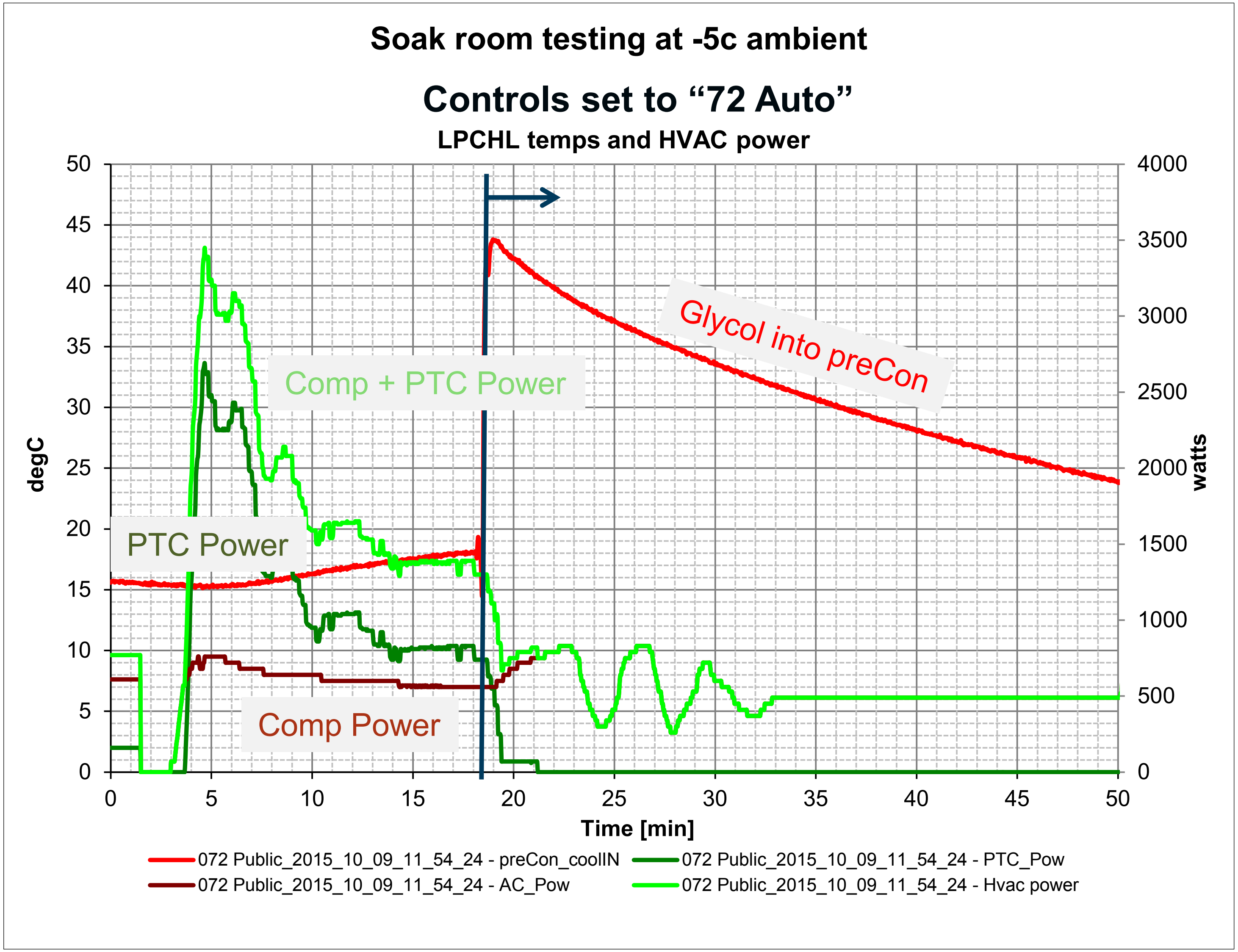
- Problem: For the hot tests, 28-43°C, using thermal storage to sub-cool refrigerant limits the amount of heat transfer and therefore the benefit (less than 1/3 of thermal storage used)
  - Solution: Introduction of a Water Cooled Condenser (WCC) that enables the use of (cool) thermal storage to aid in condensing refrigerant and thus lowers compressor discharge pressure, speed, and power

Accomplishments
Improved Coolant Loop Architecture



- Add Preconditioning (PreCon) heat exchanger to HVAC
- Add Water Cooled Condenser(WCC)
- Add two 3-way valves
- Add 4-way valve
- Add glycol heater
- Include battery (via cold plates) in glycol loop for thermal storage
- Utilize Phase Change Material (PCM) for thermal storage
- Add hoses and clamps
- Utilize insulated motor & inverter for thermal storage
- Controls for various modes

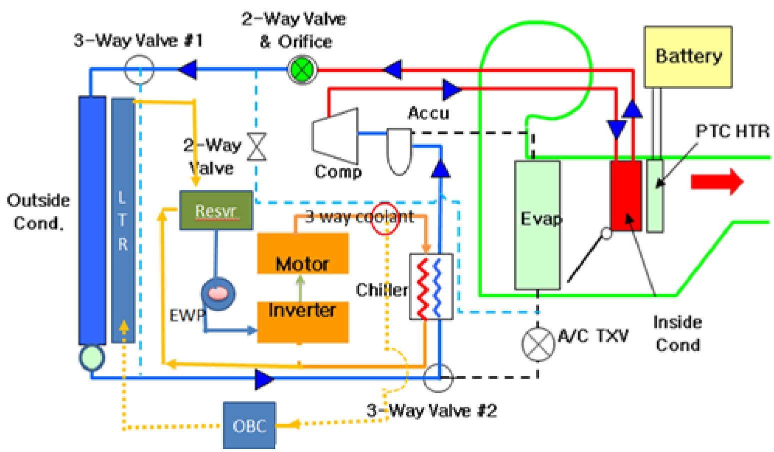
Accomplishments
Mild Cold Test (-5C)



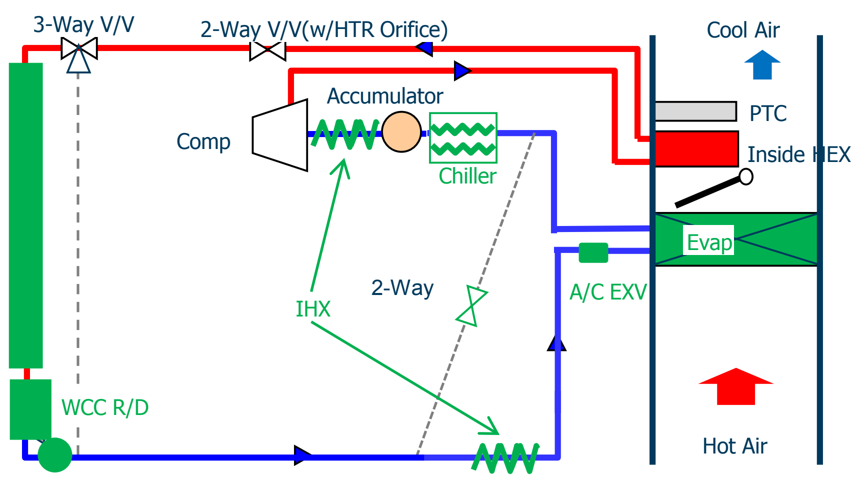
Total HVAC power reduced from ~1500 to ~500 watts

Accomplishments
Improved Refrigerant Loop Architecture

Baseline Refrigerant Loop



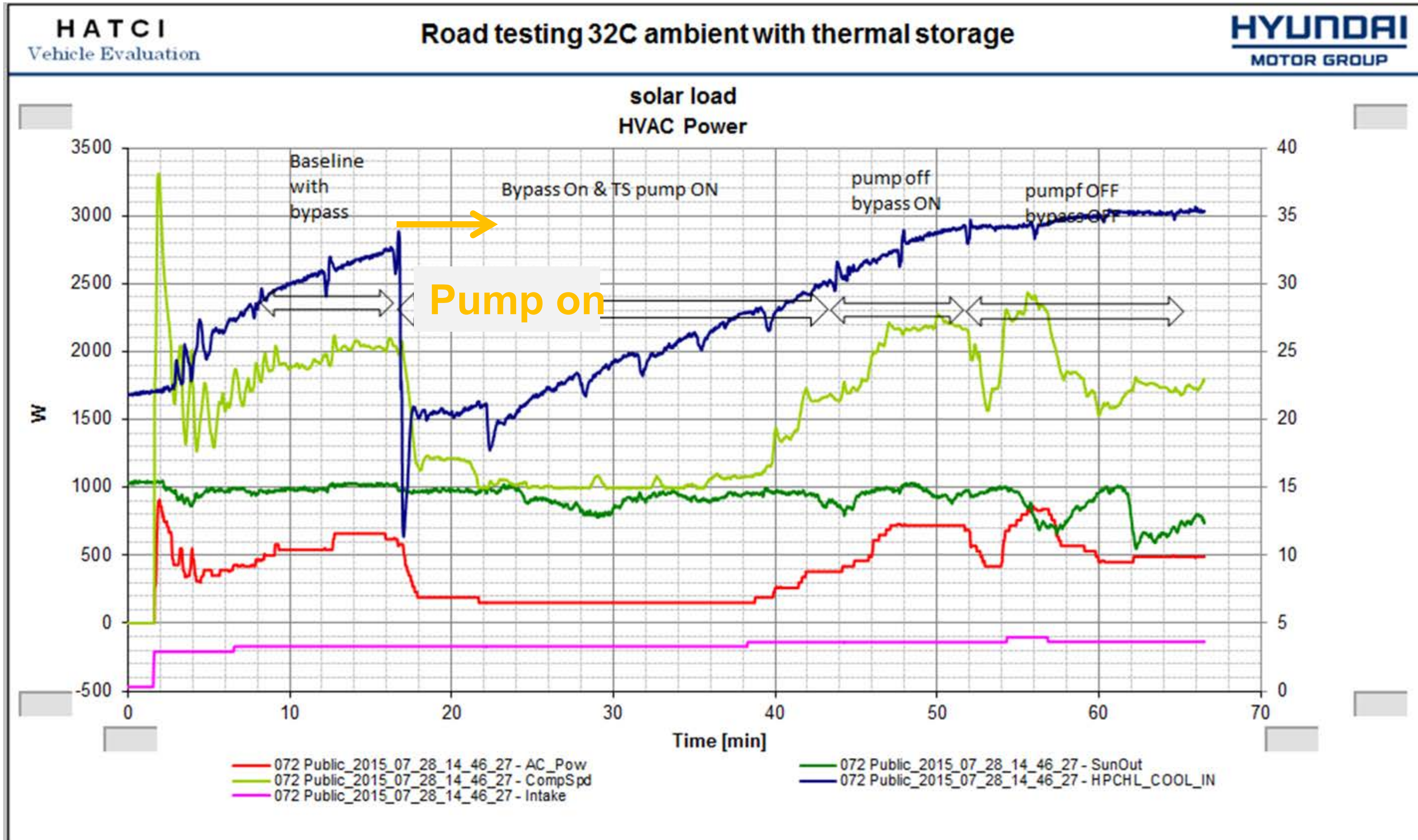
Revised Refrigerant Loop



Revisions

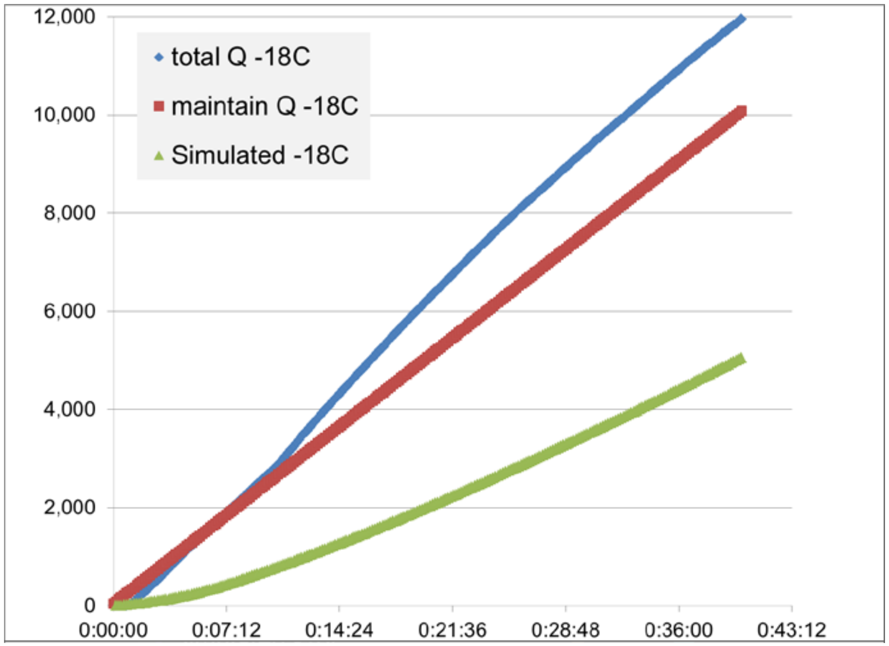
- Replace TXV with EXV
- Add Water Cooled Condenser (WCC) for harvesting “cold” storage
- Relocate chiller to be in series with evaporator
- Remove “dehumidification” line and 2-way valve
- For dehumidification, flow goes through both 2-way and AC EXV
- Replace 3-way valve before chiller/evaporator with 2-way valve as shown
- Improve heat exchanger efficiency (condenser, evaporator, internal heat exchanger)

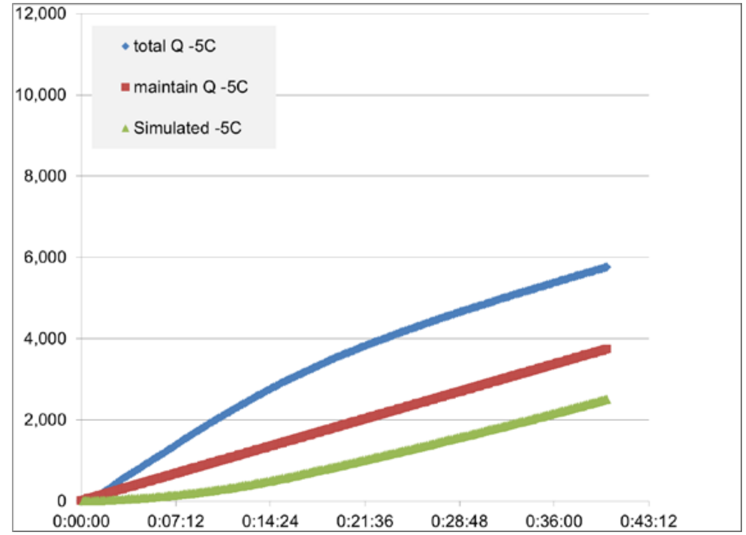
Accomplishments
Effect of Water Cooled Condenser

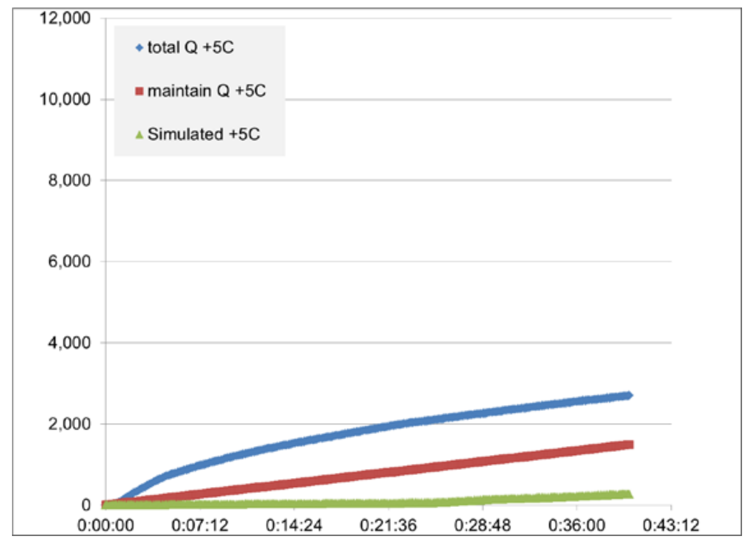


20°C glycol to WCC reduced compressor power from ~600W to ~200W

Accomplishments
System Model Predictions







Warmup vs Steady State vs Thermal Storage (model)

Accomplishments
Progress Toward Targets

- Current architecture assessment shows range extension percentages while maintaining occupant comfort

Test Condition	Target Range (%)	March 2015 Assessment (%)	Feb/March 2016 Testing (%)
Cold 3 (-18C)	9.9	15%	14%*
Cold 2 (-5C)	13.9	11%	9%
Cold 1 (5C)	13.3	3%	4.5%*
Hot 1 (28C)	9.5	6%	6%
Hot 2 (32C)	15.0	8%	9%
Hot 3 (43C)	27.2	10%	- %

Values in table assume all trips are 40 minutes. Thermal storage before each trip

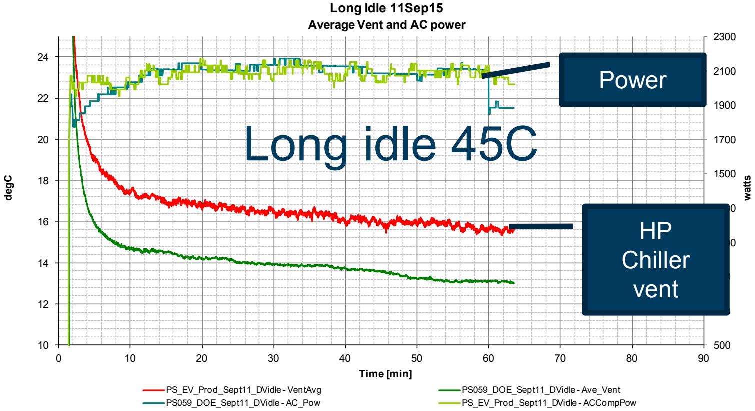
- *Issues with cold testing
  - Not able to add enough heat at -18°C
  - Not able to extract stored heat fast enough at 5°C
- For hot conditions 32C and 43C, the production refrigerant system struggles to build cold storage.

HATCI Collaboration and Coordination

Automotive OEM Partner Key Support:

- Vehicle Testing
  - Winter Test 2015
    - Built Up concept vehicle for heat storage evaluation
    - Tested in Michigan
  - Summer Test 2015
    - Tested low cost option of high pressure chiller system (good results see graph)
  - Demonstration vehicle purchased and prepared for Winter 2016 Testing
- Architecture Selection
  - Participation in brainstorming events and down-selection
  - Maintaining focus on value not just performance
- Vehicle Technology Implementation
  - Integration support of vehicle technologies and instrumentation

HATCI
HYUNDAI AMERICA TECHNICAL CENTER INC.

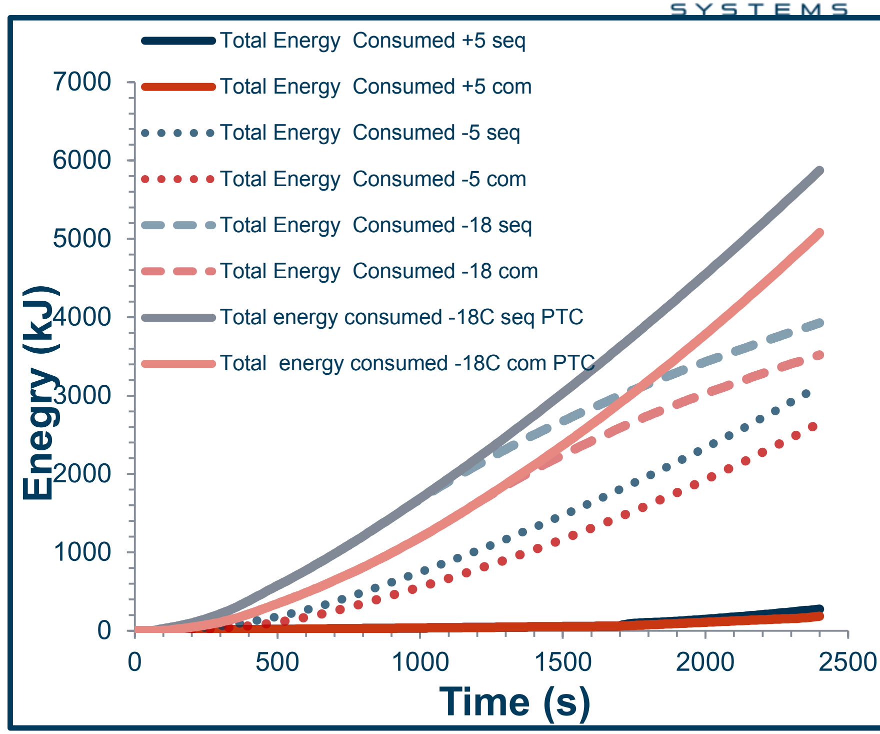


NREL Collaboration and Coordination

NREL NATIONAL RENEWABLE ENERGY LABORATORY **Thermal Modeling:**

- Models of proposed A/C and heat pump concepts were created using CoolSim framework in MATLAB/Simulink
- Heat pump modes that harvested heat stored in power electronics and electric motor (PEEM) were simulated in detail informing design decisions.
- Potential battery energy savings were estimated for each of the simulated test cases with implications to range extension.
- Combinations of modes of operations were studied including:
  - Coolant-only heat delivery from a preheated PEEM to the cabin
  - Heat pump heat delivery from a preheated PEEM to the cabin
  - Several combinations of coolant and refrigerant networks for heating the cabin.

NREL simulations helped with selection of design concepts for further testing



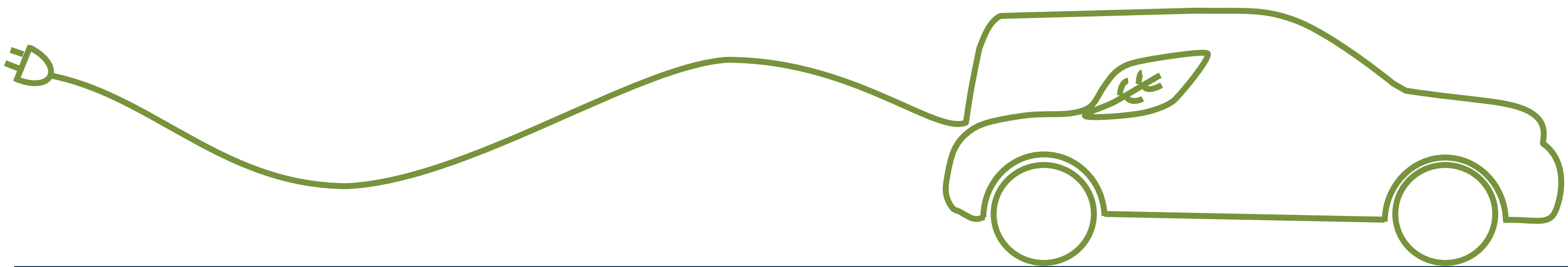
Battery energy consumption by various modes of heat delivery at three ambient temperatures (-18^{0}C, -5^{0}C and +5^{0}C).

- Sequential (seq): Initially heat from the PEEM to the cabin is delivered by coolant network and then by refrigerant based heat pump.
- Combined (com): Heat from the PEEM to the cabin is delivered by coolant network and refrigerant base heat pump simultaneously
- Heating in case of -18^{0}C is complemented by an air PTC heater when the coolant network and heat pump combined cannot supply enough capacity to the cabin

Barriers/Key Challenges

Barriers/Challenges	Roadmap
At mild cold ambient conditions, removing thermal storage quickly	• Investigate ways to increase heat transfer from glycol to refrigerant in chiller (RPM, refrigerant charge)
Incorporate new strategy with existing control logic	• Manual control of some new features may be required
Refrigerant charge management between air conditioning and heat pump operation.	• Investigate use of a check valve, control strategy, accumulator and receiver/dryer size.
Building “cold” storage at hot ambient creates: • Compressor noise • Additional heat in closed space (garage)	• Limit thermal storage
Thermal comfort model unreliable for small changes	• Investigate model improvements

Future Work



FY2016/7 Roadmap

2Q16

- Complete vetting of engineering challenge opportunities and evolution of the system
- Complete the analysis and finalize the architecture for the demonstration vehicle

3Q16

- Baseline vehicle testing
- Installation of new architecture into demonstration vehicle
- Demonstration vehicle wind tunnel testing
- Road testing – warm weather

4Q16

- Demonstration vehicle road testing – cool weather
- Final analysis and project summary

Response to Reviewer Comments

Criteria	Comment	Response
Approach	Reviewer asking if any passive load reduction elements are being considered as part of this project such as solar glazing, reflective paint, cab insulation, etc. If not, it may be good to consider them, as it could lower the overall requirements on the advanced HVAC systems.	Although it is understood that these technologies will reduce the load on the system, they are outside the scope of this project. Hanon is involved in a separate DOE co-funded project led by NREL that is investigating load reducing technologies (Design and Implementation of a Thermal Load Reduction System in a Hyundai PHEV - Project ID: VS165)
Technical Accomplishments	Reviewer commented that the analysis needs to be completed with non-grid-connected optimization systems and baseline.	Part of the design consideration and analysis is for "return trip" conditions, when being connected to the grid before the trip is not an option.
Collaboration	The reviewer stated that this would clearly be improved researching multiple OEMs and varied battery cooling strategies. The reviewer believed there is too much implied commercial system development within this project.	We agree that this effort would benefit from considering multiple battery cooling strategies. However, this project was initiated with one OEM and the resources required to consider multiple strategies were not included in the application.

Summary

- **Relevance:** Project scope addresses VTO objectives of extending electric vehicle driving range through climate load reduction, thus aiding in market adoption

- **Approach:** Team is utilizing complimentary blend of modeling and testing efforts to identify and verify load reduction and comfort acceptability

- **Accomplishments:** Systems have successfully been modified to address performance shortfalls identified in FY14. New components and systems have been evaluated in-vehicle.

- **Collaboration:** Experienced OEM and National Laboratory partners continue to contribute key knowledge and expertise towards project success

- **Future Work:** In FY16 we will fabricate final components and install final systems in the demonstration vehicle for validation evaluation

Thank You

Accelerating Innovation